First Results of SECRAL at 18GHz for Intense Beam Production of Highly Charged Ions*

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Abstract A Superconducting ECR ion source with Advanced design in Lanzhou (SECRAL) was successfully built to produce intense beams of highly charged ions for Heavy Ion Research Facility in Lanzhou (HIRFL). The ion source has been optimized to be operated at 28GHz for its maximum performance. The superconducting magnet confinement configuration of the ion source consists of three axial solenoid coils and six sextupole coils with a cold iron structure as field booster and clamping. For 28GHz operation, the magnet assembly can produce peak mirror fields on axis 3.6T at injection, 2.2T at extraction and a radial sextupole field of 2.0T at plasma chamber wall. A unique feature of SECRAL is that the three axial solenoid coils are located inside of the sextupole bore in order to reduce the interaction forces between the sextupole coils and the solenoid coils. During the ongoing commissioning phase at 18GHz with a stainless steel chamber, tests with various gases and some metals have been conducted with microwave power less than 3.2kW and it turned out the performance is very promising. Some record ion beam intensities have been produced, for instance, 810eμA of O^{7+}, 505eμA of Xe^{20+} , 306eμA of Xe^{27+}, 21eμA of Xe^{34+}, 2.4eμA of Xe^{38+} and so on. To reach better results for highly charged ion beams, further modifications such as an aluminium chamber with better cooling, higher microwave power and a movable extraction system will be done, and also emittance measurements are being prepared.

Key words SECRAL ECR ion source, superconducting magnet, highly charged ion beams

1 Introduction

A new generation fully superconducting ECR ion source named SECRAL (Superconducting ECR ion source with Advanced design in Lanzhou) was designed and built at Institute of Modern Physics to achieve the performance enhancement of HIRFL (Heavy Ion Research Facility in Lanzhou) accelerator complex[1]. The goal of the SECRAL ECR ion source project is production of intense heavy-ion beams with high charge state such as 50—100eμA of Xe^{33+}, U^{41+} dc beams and 100—200eμA pulsed beams. The other goal of the SECRAL project is to develop a compact fully superconducting ECR ion source with a new structure and high performance at 18—28GHz rf frequency.

Geller's ECR scaling laws imply that an advanced highly charged ECR ion source with excellent performance requires higher magnetic fields and higher microwave heating frequency in order to increase the

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plasma density and the ion confinement time[2]. The new magnetic scaling laws established by systematic studies at superconducting ECR ion source SERSE demonstrate the axial magnetic field at injection for a high performance ECR source should be about four times the ECR resonance field[3, 4]. These guidelines have resulted in utilization of superconducting magnet technology for higher frequency ECR ion source such as 28—56GHz. A few of fully superconducting ECR ion sources have been built and in operation, such as SERSE in Catania[4], VENUS in Berkeley[5] and SECRAL in Lanzhou[6, 7]. Some other fully superconducting ECR sources are under construction or in planning, such as European MS-ECRIS[8], RIKEN SC-ECRIS[9] and MSU SuSI[10]. SERSE and VENUS have opened an important development trend of fully superconducting ECR ion source for production of intense highly charged ion beams. Constructions of the ECR source SERSE and VENUS have addressed many of experiences and technical challenges for building a fully superconducting ECR source[11, 12]. In particular, many tests from VENUS prototype magnet demonstrate the interaction forces between the axial superconducting solenoid coils and the radial superconducting sextupole could be extremely high, which makes the superconducting magnet assembly pretty hard to build[13]. In order to reduce the interaction forces between the axial superconducting solenoid coils and the radial superconducting sextupole, and make a fully superconducting ECR source more compact and easier to build, a completely new structure for a fully superconducting magnet assembly was proposed during design of the SECRAL ECR source in 2001[14]. The key point of the innovative design for SECRAL is that the three axial superconducting solenoid coils are located inside bore of the superconducting sextupole, while the traditional coil configuration of the other fully superconducting ECR sources is reverse one, that is, the axial solenoid coils are located outside of the sextupole. This new coil configuration results in many significant advantages for a fully superconducting ECR ion source[7].

The SECRAL superconducting magnet assembly was fabricated by ACCEL Instruments from Aril 2002 to April 2005. In April 2005 the magnet reached to 100% of the design fields. The first beam of SECRAL at 18GHz was extracted and analyzed in August 2005. The ion source commissioning at 18GHz for optimization of highly charged intense beam production was conducted from August 2005 to June 2006. Many record ion beam intensities were achieved during the source commissioning. The first results at 18GHz commissioning phase are described in more detail in this paper.

2 SECRAL ECR ion source

SECRAL design and its beam transport line are illustrated in Fig. 1. The SECRAL design has been optimized for maximum ion source performance at 28GHz rf frequency for high charge state heavy ion beam production as well as for developing a compact fully superconducting ECR ion source with a new magnet structure. A detailed description of the source design and the superconducting magnet assembly can be found in references[6, 7]. The experiences from SERSE and VENUS are very helpful for design of conventional components of the SECRAL ion source. The plasma chamber was designed to be made of a double wall aluminum tube with water cooling channel in between. The inner diameter of the chamber is 126mm. But actually a stainless steel chamber is installed because the aluminum one has not been ready. The microwave guides, metallic evaporation ovens and biased disk system are inserted into the ion source through an injection vacuum tank. Almost all components inside the plasma chamber are water cooled to avoid getting hot. A 700l/s and 1600l/s turbo-molecular pump is located at injection and extraction side respectively to pump the plasma chamber.

The SECRAL superconducting magnet assembly consists of three axial solenoid coils and six sextupole coils with a cold iron structure as field booster and clamp. What is different from the traditional design is that the six sextupole coils are located outside of the three axial solenoids in order to reduce the interaction force between the sextupole coils and the solenoid coils. At full excitation, the magnet assembly reached 100% of the design fields, the peak mirror field on axis of 3.6T at injection, 2.2T at extraction and a radial sextupole field of 2.0T at the chamber wall. The superconducting magnet assembly is immersed into 4.2K liquid helium for cooling down. The cryogenics is designed to operate at low liquid helium consumption. This is realized by use of one stage cryo-cooler providing pre-cooling at 30—50K and radiation shields around the liquid helium container, and also by use of high T_c current leads that conduct electric current and minimize the heat leakage.

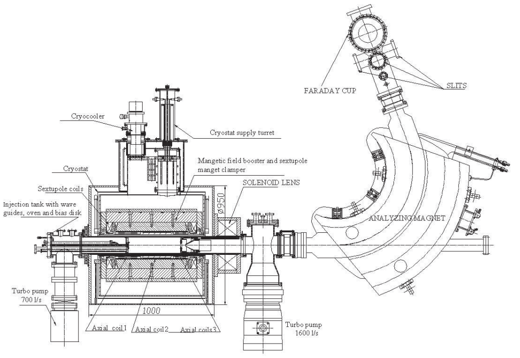

Fig. 1. Layout of SECRAL ion source and its beam transport line.

The beam transmission line is designed to transport 15mA intense highly charged heavy ion beams with high transmission efficiency and high resolution. The beam line consists of a solenoid lens and 110-degree analyzing magnet. The solenoid lens is directly attached on the extraction flange of the source body so as to focus the beam immediately after extraction[5]. Bending radius of the analyzing magnet is 600mm with pole gap 120mm. Slits and a Faraday-cup are installed at the end of the beam line to control resolution of the analyzed beam and to measure beam intensity. The cone-shaped Faraday-cup is well shielded to the ground and is water cooled through BeO insulation material. A suppressor electrode is negatively biased to 150—200V voltage to suppress the secondary electrons.

3 Commissioning results at 18GHz

After conditioning of the ion source, we focused on commissioning for production of high charge state O, Ar and Xe ion beams. Typical vacuum without plasma was 4.0×10^{-8}mbar at injection side, 3.0×10^{-8}mbar at extraction side and 1.0×10^{-8}mbar at the beam line. Typical extraction voltage is 25kV for optimization of most highly charged ions. During the first stage of the commissioning, a single 18GHz microwave generator with maximum output power 1.7kW was used. To reach better results, certainly higher microwave power is needed. So the other fraction of microwave power was fed into the ion source simultaneously from the second 18GHz microwave generator with maximum output power 1.8kW. The total maximum 3.5kW power could be fed into the source. With total input power about 3.0kW from the double 18GHz microwave generators, some record ion beam intensities were achieved by optimization of the magnetic field configuration, the gas flow rate, the biased voltage and the beam focusing, for instance, 810eμA of O^{7+}, 505eμA of Xe^{20+} , 306eμA of Xe^{27+} and son on. 810eμA of O^{7+} was produced at microwave power only 2.5kW and the field configuration as B_r=1.23T, B_{inj}=2.20T, B_{ext}=1.36T, B_{min}=0.46T. 505eμA of Xe^{20+} was produced at microwave power 2.85kW and the field configuration as B_r=1.09T, B_{inj}=2.23T, B_{ext}=1.27T, B_{min}=0.47T. 306eμA of Xe^{27+} was produced at microwave power 3.1kW and the field configuration as B_r=1.29T, B_{inj}=2.52T, B_{ext}=1.41T, B_{min}=0.53T. Fig. 2 and Fig. 3 show the spectra with the source optimized on $O^{7+}$and Xe^{27+} respectively.

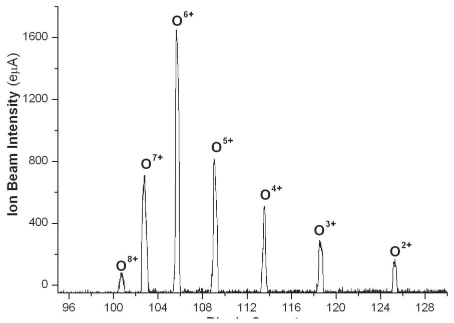

Fig. 2. CSD spectrum with the source optimized on O^{7+} at 2.0kW.

Table 1 shows some of the commissioning results from SECRAL and compares beam intensity with other high performance sources for reference.

Fig. 4 illustrates beam intensity dependence of different charge state Xe ions on the coupled microwave power, which demonstrates the highly charged xenon beam intensities keep increasing with the coupled microwave power, and it is far from saturation. All the results from SECRAL shown in Table 1 were achieved with the microwave power density less than 0.65kW/l (SECRAL plasma chamber volume is about 5l). To achieve optimum results, the expected power density coupled into SECTAL should reach about 1.0—1.2kW/l for 18GHz.

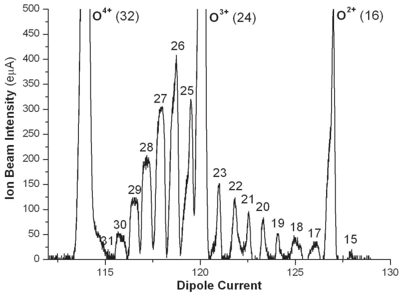

Fig. 3. CSD spectrum with the source optimized on Xe^{27+} at 3.1kW.

Table 1. Commissioning results of SECRAL at 18GHz in comparison with other high performance ECRIS.

f/GHz		SECRAL	VENUS[5, 15]	SERSE[4]	GTS[16]
		18	28 or 28+18	28	18
^{16}O	6^+	2300	2850		1950
	7^+	810	600		
^{40}Ar	11^+	810			510
	12^+	510	860		380
	14^+	270	514		174
	16^+	73	133		50
	17^+	8.5	14		4.2
^{129}Xe	20^+	505	320	390	310
	25^+			216	
	26^+	410	290		228
	27^+	306	270		168
	28^+		222		120
	30^+	101	116	100	60
	31^+	68	67		40
	33^+	31			15
	34^+	21	15		8
	35^+	12			5.4
	37^+	5			2.3
	38^+	2.4			1

To demonstrate capability of metallic ion beam production for SECRAL, within 10 days we quickly tested productions of highly charged Ca, Ni and Pb ion beams with a high temperature oven dedicated for SECRAL, which can reach more than 1600℃. With the high temperature oven inserted into the SECRAL source, the coupled microwave power is limited to maximum 1.7kW because only one waveguide from single microwave generator is available. However, some promising results were achieved for metallic ion beam production, for instance, 287eμA Ca^{11+}, 75eμA Ca^{16+}, 18eμA Ca^{18+}, 2.25eμA Ca^{19+}, 173eμA Pb^{27+}, 143eμA Pb^{28+} and 90eμA Pb^{30+}. Anyway, it is impossible to have very good results for three kinds of metallic ion beam productions within only 10 days. So the results of metallic ion beam production remain very preliminary.

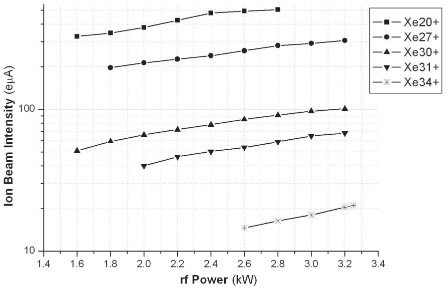

Fig. 4. Dependence of Xe ion beam intensities on the coupled microwave power.

Commissioning results and measurements indicate the beam transport line has reached nice transmission efficiency. Here is an example. During the SECRAL source optimized on O^{6+} beam production with the total drain current 10emA at extraction voltage of 20kV, the measured O^{6+} current is about 1.5emA. The total beam transmission into the Faraday-cup is estimated more than 85%.

Liquid helium consumption of the SECRAL superconducting magnet is another important issue. During SECRAL commissioning, it is found the liquid helium consumption depends on the coupled microwave power for certain magnetic field configuration, which may be caused by additional heat load from strong X ray of the ECR plasma. Roughly, when the coupled microwave power is 1.0—2.0kW at 18GHz, the liquid helium consumption is about 1.5 l/h. While the coupled power is 2.5—3.0kW, the liquid helium consumption could be raised up to 2.5l/h. There is helium gas recycling system in operation.

4 Conclusion and discussion

A new generation fully superconducting ECR ion source SECRAL with an innovative structure has been successfully built. Commissioning results at 18GHz demonstrate that the performance of intense highly charged ion beam production is very promising. Some record ion beam intensities have been produced at 18GHz and microwave power less than 3.2kW. However, all the results presented in this paper should be viewed as an initial stage of the SECRAL test because of the following reasons. Firstly, SECRAL was designed to operate at 28GHz microwave frequency for maximum performance of highly charged ion beam production. Certainly higher microwave power is needed for optimum results, at least as high as 5—6kW for both 18GHz and 28GHz. Secondly, at the moment SECRAL is still using stainless steel chamber. The plasma chamber made of aluminum should enhance production of highly charged ion beams. An aluminum chamber for SECRAL is under fabrication although it is very hard for us.

During SECRAL commissioning for intense beam production at 25kV extraction voltage, the main insulator between the plasma chamber and the magnet was ever burned a hole. The damage position is corresponding to the axial minimum-B at off-axis. As Dr. lyneis ever pointed out[17], this damage could be resulted from the strong X ray emitted by the hot electrons of the plasma at the position. Similar to VENUS[18], it implies a tantalum shielding between the plasma chamber and the insulator is necessary for the new aluminum chamber. The shielding may be also effective to reduce liquid helium consumption.

SECRAL was already installed at the axial injection beam line of IMP cyclotron. It is ready to provide intense beams for the cyclotron operation. The next step of the SECRAL test will focus on metallic ion beam production and effect of the magnetic field configuration on the ion source performance and beam emittance. An aluminum chamber and a moveable extraction system will be installed when they are ready. SECRAL test at 24—28GHz will be a future plan which depends on financial support.

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